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Generation of electrical short pulse using Schottky line periodically loaded with electronic switches

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A method of the generation of an electrical short pulse, which uses the Schottky line periodically loaded with electronic switches as a key device, is proposed. As is well known, the Schottky line, which means a transmission line periodically loaded with Schottky diodes, simulates the Toda lattice. When a pulse with the longer temporal duration than the inverse of the Bragg frequency of the line is inputted, it is split to be several solitons. Moreover, these solitons have in general shorter temporal duration than the input pulse. We consider the case in which an electronic switch (the switch is open for voltages greater than some fixed threshold, and closed otherwise) is put in parallel with each Schottky diode. Once the input pulse crosses the threshold voltage of the shunt switches, this multiple solitons are all attenuated at the voltages below the threshold by the finite conductance. However, it is found that the larger solitons are less attenuated than the smaller ones. Thus, it is possible to obtain only the largest soliton among the multiple ones, when we obtain the output after the appropriate transmission of the pulse on the proposed nonlinear transmission line. In this paper, we describe the principle of the operation of the proposed method and quantify how well the method succeeds in the generation of short pulses through both the perturbative characterization and the numerical integration of the transmission equation of the line. © 2006 American Institute of Physics. [DOI: 10.1063/1.2210269]

I. INTRODUCTION

Generation of a short electrical pulse with picosecond duration is one of the keys to produce a breakthrough in high-speed electronics. The applications of short pulses include measurement system with picosecond temporal resolution, over 100 Gbit/s communication systems and submillimeter-to-terahertz imaging systems.

Recent trend in ultrashort-electrical-pulse generation is the employment of broadband optical-to-electrical converting devices with short pulse laser. State-of-the-art device gives electrical pulses with <1.5 ps duration.¹ Although the introduction of photonic technologies is very effective, the purely electronic generation method is strongly needed. This is because the photonic method costs so much and is very difficult to provide compact systems. As for the purely electronic pulse generation, the intensive works carried out by the UCSB group in mid-1990s are noteworthy.² As is well known, the Schottky line supports solitons through the regularly spaced capacitors whose capacitance is inversely proportional to the line voltage.³ Moreover, pulses input to the Schottky line will be split to be multiple solitons. The pulse duration of each soliton is generally shorter than that of the initial pulse, so that it is possible to succeed in the generation

of the short electrical pulse by getting one of multiple solitons. UCSB group designed the elaborating Schottky line, which was the cascade of two sections having different cut-off frequencies,⁴ in order to obtain highly compressed electrical impulse. However, in their approach, there was a need to set an upper limit on the number of solitons to be generated for the sake of the preservation of the pulse shape. The compression ratio was also limited.

Our method also uses this engineered utilization of the initial value problem of the solitonic pulse propagation. However, no limitations are needed to be set on the number of solitons generated by the transmission along the line. It then becomes possible to design the Bragg frequency of the line as high as possible, so that we can get highly compressed or ultrashort pulses. The method requires electronic switches being implemented in parallel with shunt Schottky diodes in the line and setting the input pulse to cross the threshold voltage of the loaded switches. Hereafter, we call the Schottky line with electronic switches the *modified Schottky line* for brevity. Moreover, we use the convention that the line voltage becomes greater when the loaded Schottky diodes are more reversely biased. We then found that the larger solitons are less attenuated than the smaller ones. Thus, it is possible to get only the largest soliton of the multiple ones independently of their number.

This paper is organized as follows. In Sec. II, we pro-

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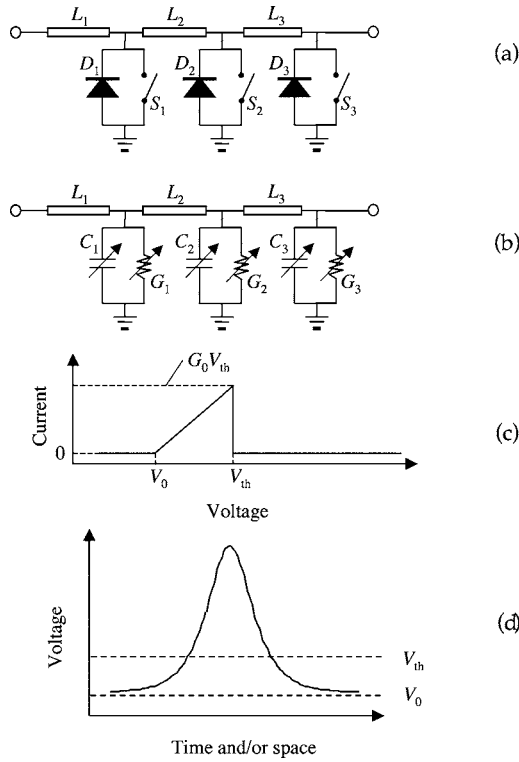


FIG. 1. Definition of modified Schottky line. (a) Circuit diagram, (b) equivalent representation, (c) I - V characteristics of switch conductance, and (d) development of pulse.

pose the method of the generation of a short electrical pulse together with several definitions and fundamental characteristics of the modified Schottky line. In Sec. III, we develop its model for the perturbative treatment, by which we clarify the relationship between the amplitude of the soliton and the degree of the attenuation in the modified Schottky line. In Sec. IV, we show the results of the numerical integration of the transmission equation of the modified Schottky line to verify the effectiveness of the proposed method.

II. FUNDAMENTAL CHARACTERISTICS OF MODIFIED SCHOTTKY LINE

Figure 1(a) shows the circuit diagram of the modified Schottky line. Three sections are shown. The line is periodically loaded with the Schottky diodes D_i and electronic switches S_i . A pulse is applied at an end of the line and the output is obtained at the other end. The dc bias V_0 in Fig. 1(a) gives the floor level of the applied pulse. Moreover, the pulse is inputted in a way that the Schottky diodes are reversely biased at its peak. Figure 1(b) shows the equivalent representation of the modified Schottky line, where L , C , and G show the series inductor, the shunt capacitor, and the shunt conductance of the unit section, respectively. The periodically loaded Schottky diodes are equivalently represented by C , which are dependent on the applied voltage. The capacitance is determined by the thickness of the depletion layer formed at the metal-semiconductor interface and increases in proportion to the inverse of the applied voltage. As stated above, we use the convention that the voltage becomes

greater when the Schottky diodes are more reversely biased. Thus, we specify the voltage dependence of C as

$$C(V_n) = \frac{Q_0}{V_n + V_0}, \quad (1)$$

where V_n and Q_0 are the voltage at the n th node and the charge stored in the diode capacitor at $V=0$, respectively. On the other hand, the periodically loaded electronic switches are equivalently represented by G . The conductance of the switch is defined as

$$G(V_n) = G_0 \theta(V_{th} - V_n) \theta(V_n - V_0), \quad (2)$$

where $\theta(V)$ shows the Heaviside function. The I - V characteristics of the switch is shown in Fig. 1(c). The conductance of the switches causes a finite attenuation of propagating solitons at the voltage being *less* than V_{th} . Resonant tunneling diodes (RTDs) without any thermally induced currents are the best candidates for the electronic switches. The proposed method requires that the input pulse crosses the threshold voltage V_{th} of the switches, as shown in Fig. 1(d).

It is well known that the transmission characteristics of the Schottky line are described by the Toda equation, which supports solitonic pulse propagation.^{3,5} That is, its transmission equation is given by

$$\frac{d^2}{dt_1^2} \ln(1 + u_n) = u_{n-1} - 2u_n + u_{n+1}, \quad (3)$$

where $u_n = V_n/V_0$ and $t_1 = t/\sqrt{LQ_0/V_0}$, respectively. As is well known, this equation has soliton solutions with the form of

$$u_n = -\sinh^2 k \operatorname{sech}^2(kn - \omega t_1), \quad (4)$$

$$\omega = \pm \sinh k. \quad (5)$$

As is evident, the pulse width, the amplitude, and the velocity of a single soliton are given by k^{-1} , $\sinh^2 k$, and $\sinh k/k$, respectively. Moreover, when the pulse width of the soliton is much greater than the lattice spacing, the Toda equation is reduced to the Korteweg-de Vries (KdV) equation. For simplicity, we apply this long-wavelength approximation hereafter. For the approximation, the discrete coordinate n is replaced by the continuous form x and u_n is series expanded as follows:

$$u_n = \sum_i \epsilon^i \psi^{(i)}(x), \quad (6)$$

for $\epsilon \equiv k^2 \ll 1$. We then carry out the following transformations:

$$\eta = \sqrt{2}\epsilon^{1/2}(x - t_1), \quad (7)$$

$$\tau = \frac{\sqrt{2}}{12}\epsilon^{3/2}t_1. \quad (8)$$

From the $O(\epsilon^3)$ terms, we obtain the KdV equation,

$$\frac{\partial \varphi}{\partial \tau} - 6\varphi \frac{\partial \varphi}{\partial \eta} + \frac{\partial^3 \varphi}{\partial \eta^3} = 0, \quad (9)$$

where $\psi^{(1)}$ is renamed as φ . The initial value problem of the KdV equation can be precisely solved.⁶ By solving the ei-

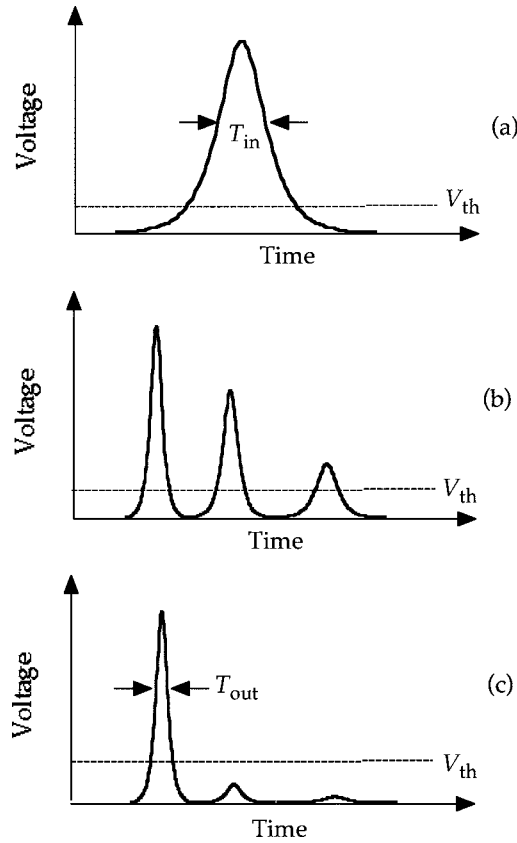


FIG. 2. Proposed method of short-pulse generation. (a) Input to Schottky line, (b) midpoint, and (c) output.

genvalue problem of the Schrödinger equation, where the function form of a pulse input to the Schottky line is represented as a potential term, the discrete eigenvalues give half of the amplitudes of the solitons generated by the initial pulse as the propagation distance increases. Moreover, the input pulse will be split to be multiple solitons, the number of which is determined by that of the eigenvalues. This process is shown in Figs. 2(a) and 2(b). This example shows the case when the input pulse is split to be three solitons, all of which have shorter durations than the input pulse. This process succeeds in the generation of short pulses, but is insufficient in that almost all engineered applications do not require the multiple uneven pulses but a single one. In the following sections, we show that the amount of the attenuation of the solitons propagating on the modified Schottky line caused by the switch conductance greatly depends on their amplitude. The larger the amplitude of the soliton becomes, the further it can propagate on the modified Schottky line. Thus, we can obtain only the largest and the shortest solitons among the multiple uneven ones through its propagation on the modified Schottky line, as shown in Fig. 2(c). This is the principle of the operation in the proposed method of short-pulse generation.

III. PERTURBATIVE ANALYSIS OF MODIFIED SCHOTTKY LINE

To quantify the amount of the attenuation of the solitons, we develop a perturbative model of the modified Schottky line with electronic switches. Figure 3(a) shows the line volt-

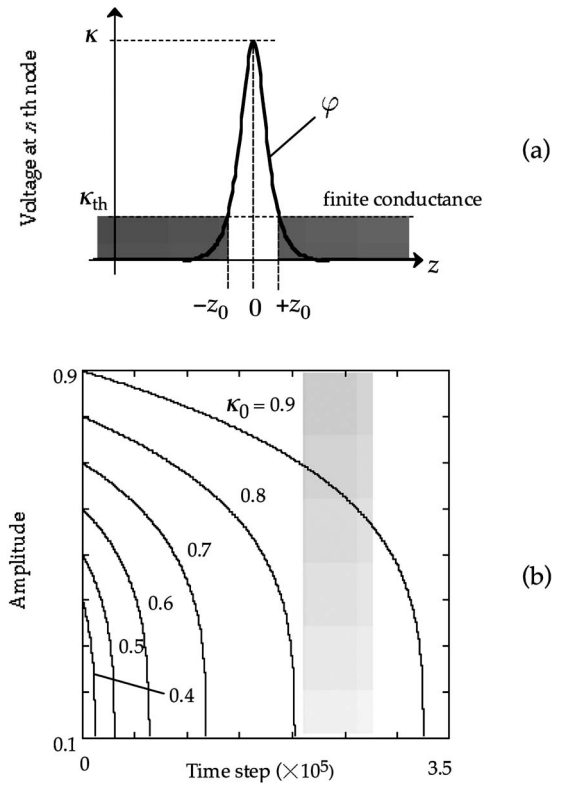


FIG. 3. Perturbation model of solitonic pulse on Schottky line. (a) Voltage at the n th node and (b) temporal change in soliton amplitude.

age at the n th node of the line. Then, by considering Kirchhoff's law at the n th node of the circuit shown in Fig. 1(b), we obtain

$$\frac{d^2}{dt_1^2} \log(1 + u_n) + G(u_n)Z_0 \frac{du_n}{dt_1} = u_{n+1} - 2u_n + u_{n-1}, \quad (10)$$

where $Z_0 (= \sqrt{L/C_0})$ is the characteristic impedance of the line at $V_n = V_0$.

We treat the second term in the left-hand side (LHS) of this equation perturbatively, so that we apply the long-wavelength approximation. That is, we carry out the transformations shown in Eqs. (7) and (8) to Eq. (10), we then obtain the following perturbed KdV equation from the $O(\epsilon^3)$ terms:

$$\frac{\partial \varphi}{\partial \tau} - 6\varphi \frac{\partial \varphi}{\partial \eta} + \frac{\partial^3 \varphi}{\partial \eta^3} = -\beta \theta(\varphi - \kappa_{th})\varphi, \quad (11)$$

where $\kappa_{th} = V_{th}/V_0$. Moreover, β is the transformed dimensionless conductance which is explicitly given by $\epsilon^{-3/2}G_0Z_0$. It turns out that the contribution of the voltage-dependent conductance of shunt switches to solitons is described by the perturbation term in the right-hand side (RHS) of Eq. (11).

The KdV equation, Eq. (9), has a soliton which is explicitly described as

$$\varphi = -2\kappa^2 \operatorname{sech}^2 z, \quad (12)$$

$$z = \kappa(\eta - 4\kappa^2 \tau). \quad (13)$$

In the framework of the perturbation theory based on inverse scattering transformation, the explicit temporal develop-

ments of the soliton parameter κ , which are originally time invariant, are obtained. For the present case, the temporal development of κ can be given as⁷

$$\frac{d\kappa}{d\tau} = \frac{\beta}{4\kappa} \int_{-\infty}^{\infty} dz \theta(\varphi - \kappa_{th}) \varphi \operatorname{sech}^2 z. \quad (14)$$

The situation is shown in Fig. 3(a). We denote the z coordinates of the cross points of $\varphi(z)$ and κ_{th} as $\pm z_0$, which are explicitly given by

$$z_0 = \tanh^{-1} \left(1 - \frac{\kappa_{th}^2}{\kappa^2 + \kappa \sqrt{\kappa^2 - \kappa_{th}^2}} \right). \quad (15)$$

Then, the Heaviside function that appeared in Eq. (14) is equivalent to $\theta(z - z_0) + \theta(-z_0 - z)$, thus we obtain

$$\frac{d\kappa}{d\tau} = -\frac{\beta\kappa}{2} \left[-2 \tanh z_0 \left(1 - \frac{1}{3} \tanh^2 z_0 \right) + \frac{4}{3} \right]. \quad (16)$$

Figure 3(b) shows the results of numerical integration of Eq. (16) for several different initial values of κ [denoted by κ_0 in Fig. 3(b)]. The threshold voltage κ_{th} was set to 0.1 and κ_0 was varied from 0.4 to 0.9 by 0.1. As shown in Fig. 3(b), the degree of the attenuation in the amplitude greatly depends on κ_0 . Moreover, the large soliton is less and less attenuated than the small one. The temporal span the soliton can survive seems to increase exponentially as the amplitude increases. It is then expected that we can obtain only the soliton with κ_0 of 0.9, when the line length of the modified Schottky line is designed to give output in the hatched region in Fig. 3(b), even if the input pulse is split to be any other solitons having κ_0 of <0.9 . Note that the length of the unit section is normalized to be unity in the present notation so that κ is dimensionless. In order to obtain the temporal pulse width in the real scale, we only divide κ^{-1} by the cutoff frequency, $1/\sqrt{V_0/LQ_0}$. As discussed above, the initial value problem of the KdV equations is reduced to the eigenvalue problem of the Schrödinger equation. For example, when a triangular pulse having a rise and a fall times of 10 ps is inputted to the modified Schottky line with the cutoff frequency of 200 GHz, the numerical evaluation of the eigenvalue problem results in the generation of five uneven solitons, together with the radiation modes, which correspond to the continuous eigenvalues. Each soliton has the amplitude (width) of 15.8 (2.5 ps), 7.1 (3.0 ps), 3.1 (3.8 ps), 0.85 (5.2 ps), and 0.1 (10.2 ps), respectively. The amplitude of the first soliton is greater than twice that of the other ones, so that it is expected to obtain only the first soliton by the application of our method. On the other hand, the radiation modes are all attenuated away through the propagation, because their amplitudes are in general much smaller than those of uneven solitons to be less than κ_{th} . Thus, the method succeeds in the generation of the short pulse having the temporal width of 2.5 ps for the present example.

IV. NUMERICAL EVALUATION

The perturbative theory only predicts solitonic behavior under several assumptions. To discuss more realistic situations, we numerically solved the transmission equations of

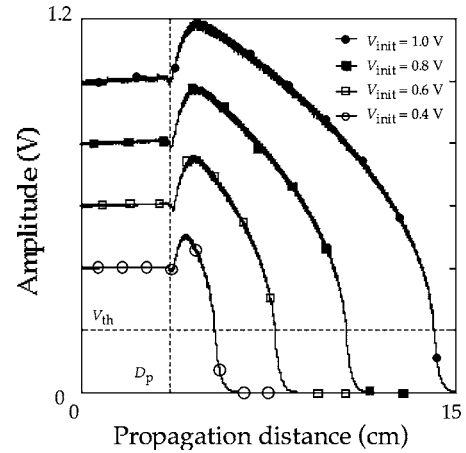


FIG. 4. Numerically obtained spatial change in soliton amplitude.

the modified Schottky line. For the calculations, the shunt capacitance per unit length was set to voltage-dependent function given by Eq. (1) with $Q_0 = 30.0$ pC/mm and $V_0 = 20.0$ V. Moreover, the shunt conductance per unit length was also set to be voltage dependent as in Eq. (2) with $V_{th} = 0.2$ V and $G_0 = 0.05$ S/mm. The series inductance per unit length L was set to 0.5 nH/mm, and the series resistance was neglected. The length of the unit section D was 50 μ m.

First, we verify the dependence of the attenuation on the soliton amplitude. To see the behavior of the propagation characteristics of the single soliton, we apply the hyperbolic secant wave form with the full width at half maximum (FWHM) of $W_0 \equiv D\sqrt{LQ_0/V_{init}}$ (V_{init} : amplitude of input pulse), which corresponds to the single soliton solution of the modified Schottky line. The first segment of the line with the length of $D_p = 3.6$ cm was the ordinary Schottky line, so that the input pulse propagates along it as the unperturbed soliton. This arrangement is for seeing the effect of the voltage-dependent conductance to the ideal solitons.

Figure 4 shows the change in the amplitude of the solitonic pulses with respect to the propagation distance for each initial amplitude of 0.4, 0.6, 0.8, and 1.0 V. It is very interesting that the soliton gains amplitude at the very early stage of the propagation on the modified Schottky line. As mentioned above, the amplitude of the soliton is inversely proportional to its width, so that this nonperturbative behavior may be caused by the reduction of the pulse width by the conductance. The amount of the voltage gain seems to increase as V_{init} increases, thus this behavior may help our method of the single pulse generation. On the other hand, the amount of the attenuation becomes smaller when the amplitude of the soliton becomes greater as predicted by the perturbative treatment. The characteristics of the amplitude of the soliton shown in Fig. 4 is really similar to that in Fig. 3(b). The fact that the large soliton is less attenuated by the line conductance than the small one is well confirmed by both the perturbative and the nonperturbative characterizations of the pulse propagation along the modified Schottky line.

Second, we demonstrate the generation of single pulse using the modified Schottky line. Figure 5 shows this. The line parameters are the same as described above. The input

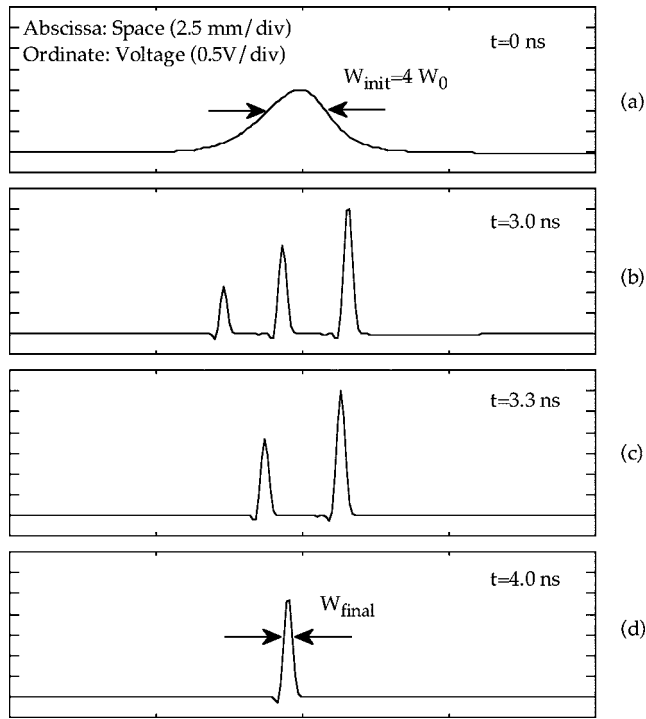


FIG. 5. Demonstration of short-pulse generation. (a) Wave form at $t=0$ ns, (b) wave form at $t=3.0$ ns, (c) wave form at $t=3.3$ ns, and (d) wave form at $t=4.0$ ns.

pulse was the hyperbolic secant having V_{init} of 1.5 V and a FWHM of $W_{\text{init}}=4W_0$, as shown in Fig. 5(a). The pulse is split to be three solitons for the present case, as shown in Fig. 5(b). Through further propagation along the modified

Schottky line, the smallest soliton of the three is first attenuated away, as in Fig. 5(c). Finally, we succeed in obtaining only the largest of the three, as in Fig. 5(d). Moreover, the final pulse width W_{final} is estimated to be $<0.1W_{\text{init}}$. We can obtain higher pulse compression ratio than the present example, through the elaborating design of the characteristic impedance, the Bragg frequency, and the threshold voltage of the modified Schottky line.

V. CONCLUSIONS

We proposed a method of the generation of the electrical-short pulse with the modified Schottky line. By simply setting the voltage level of the input pulse to cross the threshold of the modified Schottky line, we get only the largest and the shortest solitons among the ones generated by the transmission on the modified Schottky line. A pulse propagation on the modified Schottky line is perturbatively treated so that we found that the soliton with a larger amplitude is exponentially less attenuated. Moreover, we successfully demonstrated the short-pulse generation using the proposed method through the numerical integration of the transmission equation of the modified Schottky line.

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